

A dramatic photograph of a Space Shuttle launching at night. The shuttle is positioned vertically, ascending from a launch pad. A massive, bright orange and yellow plume of fire and white smoke billows from the base of the shuttle, illuminating the scene. The launch pad's service structure is visible on the left side of the frame. The background is dark, with some wispy clouds illuminated by the shuttle's engines.

Space Shuttle Reusable Solid Rocket Motor

*Chief Engineers Council
Montreal Canada
August 24-26, 2010*

*Dennis Moore/MSFC
Jack Phelps/MSFC
Fred Perkins/ATK*



AGENDA

RSRM Accomplishments – Jack Phelps

- ◆ *SRM/RSRM Evolution*
- ◆ *Insulation J-Leg*
- ◆ *Improved Resiliency O-rings/Gaskets*
- ◆ *ETM-3 – Five Segment Margin Test*
- ◆ *Carbon Fiber Rope*
- ◆ *ATK BSM*

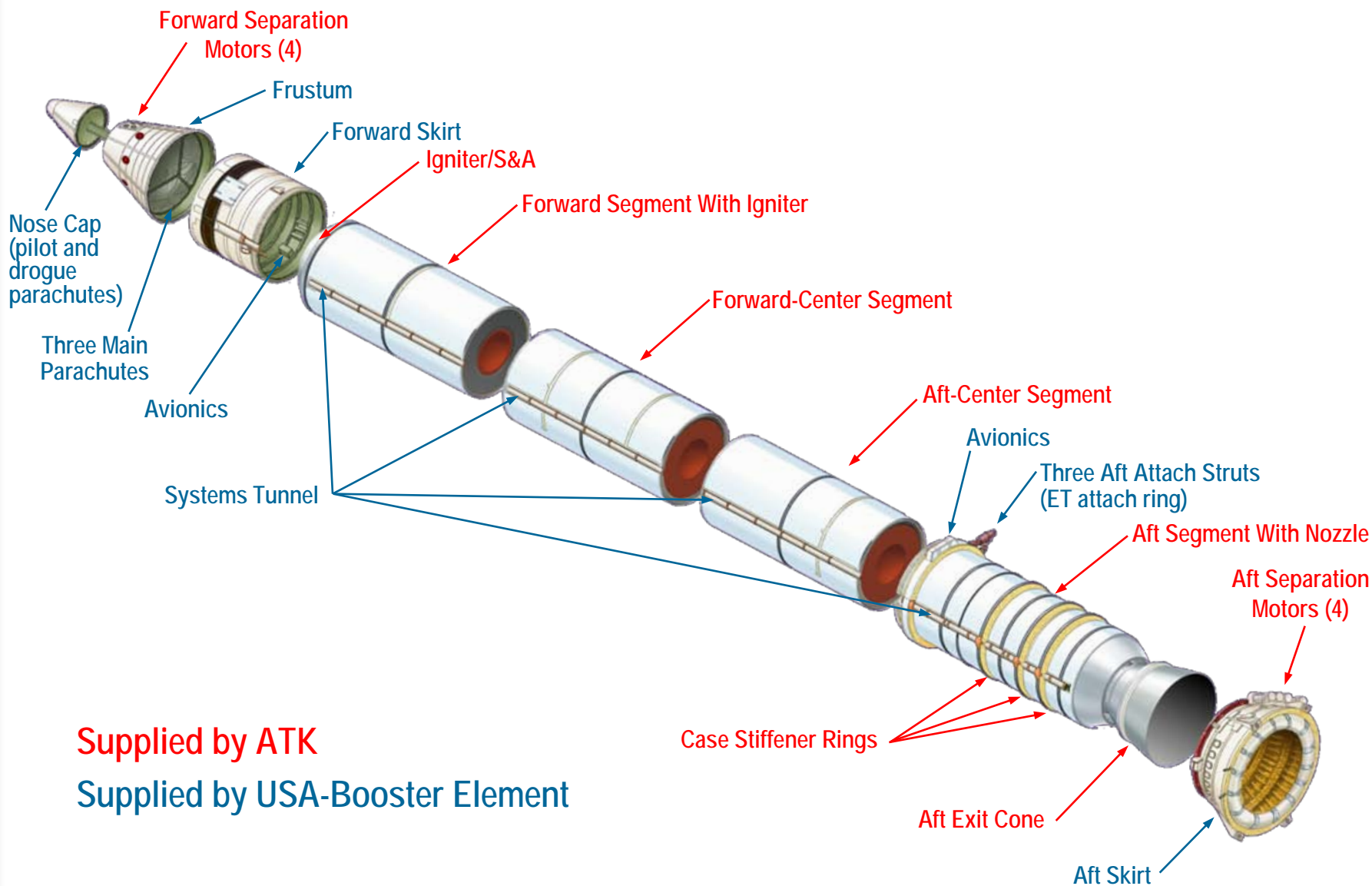
RSRM Lessons Learned – Fred Perkins

- ◆ *Nozzle Pocketing*
- ◆ *Field Joints and Nozzle-to-Case Joint*
- ◆ *Pressure Sensitive Adhesive*
- ◆ *RSRM Evolved Toolbox*

RSRM Culture – Dennis Moore

- ◆ *RSRM Test Program*
- ◆ *RSRM Postflight*
- ◆ *7 Elements of Good Flight Rationale*
- ◆ *Some Thoughts on Minority Opinions*
- ◆ *Summary*

Booster/Motor



Supplied by ATK

Supplied by USA-Booster Element

RSRM Accomplishments

JACK PHELPS



- ◆ SRM/RSRM Evolution
- ◆ Insulation J-Leg
- ◆ Improved Resiliency O-rings/Gaskets
- ◆ ETM-3 – Five Segment Margin Test
- ◆ Carbon Fiber Rope
- ◆ ATK BSM

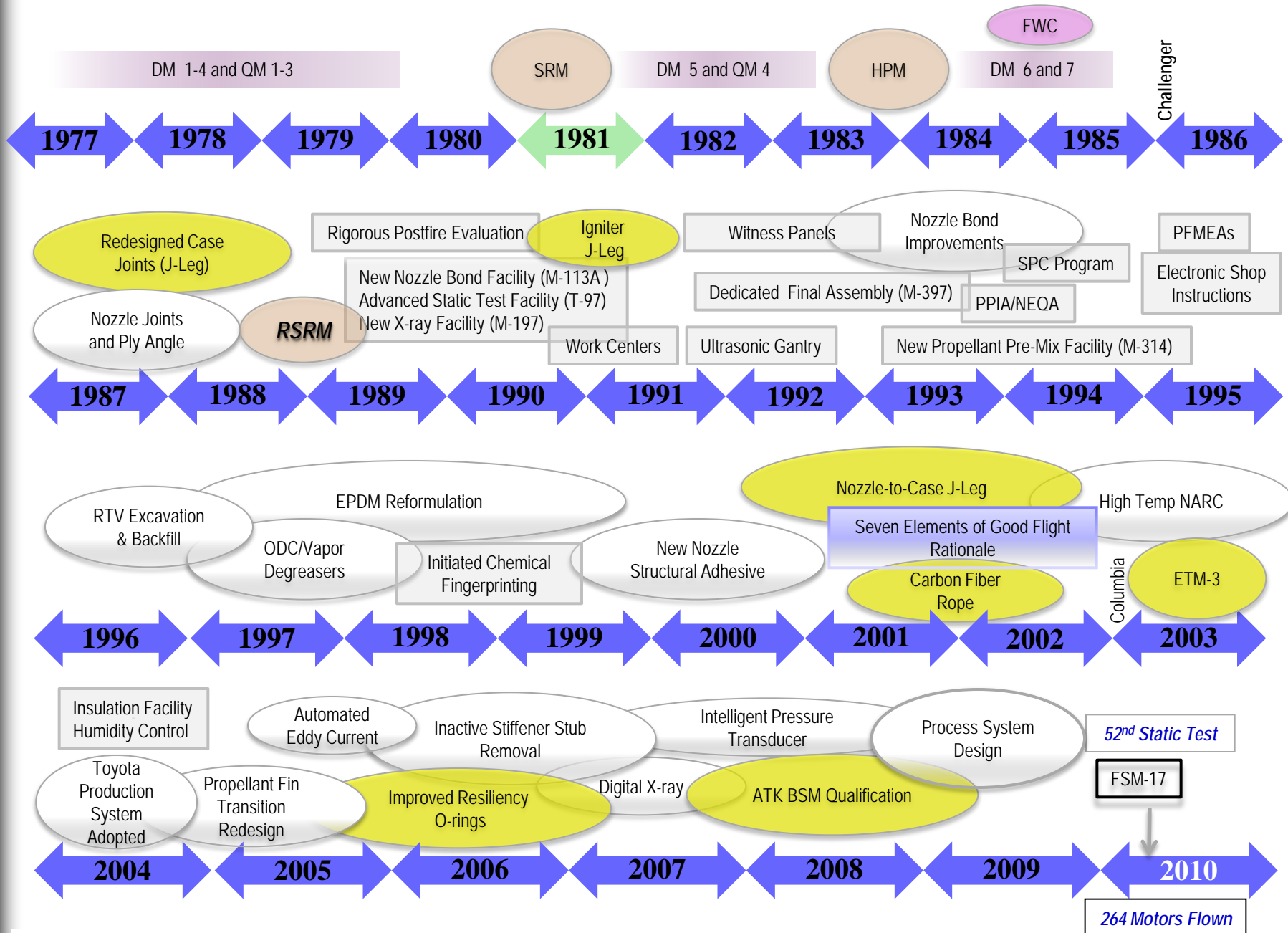




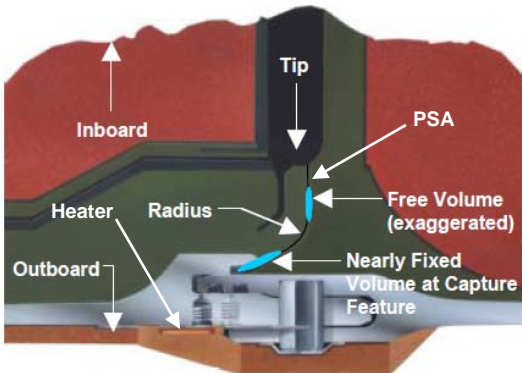
ACCOMPLISHMENTS

SRM/RSRM EVOLUTION

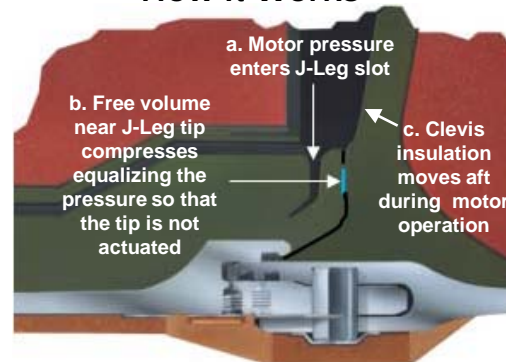
JACK PHELPS



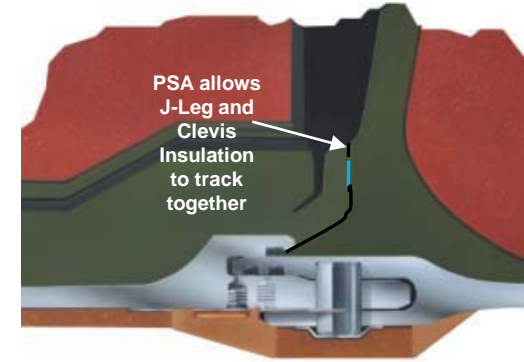
How it Works



1. Prior to Motor Operation

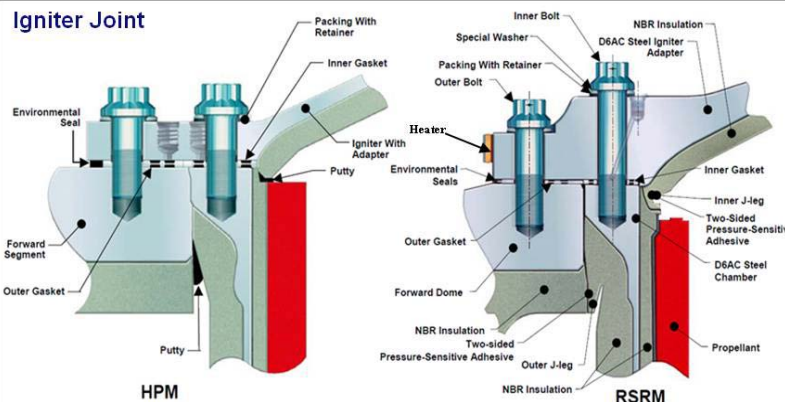


2. Ignition



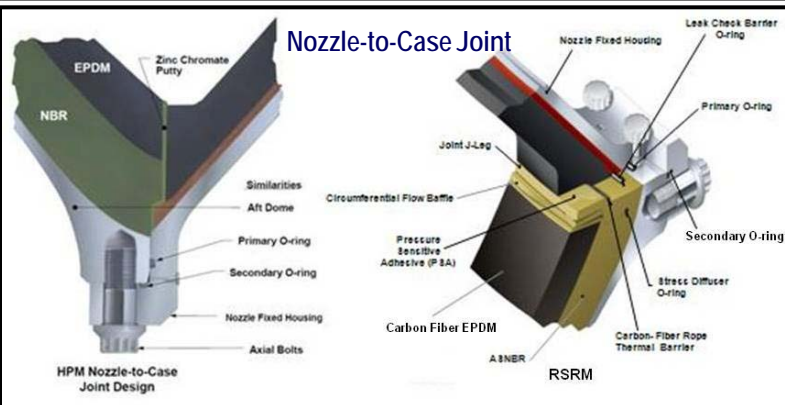
3. PSA keeps J-Leg adhered to Clevis Insulation

Igniter Joint

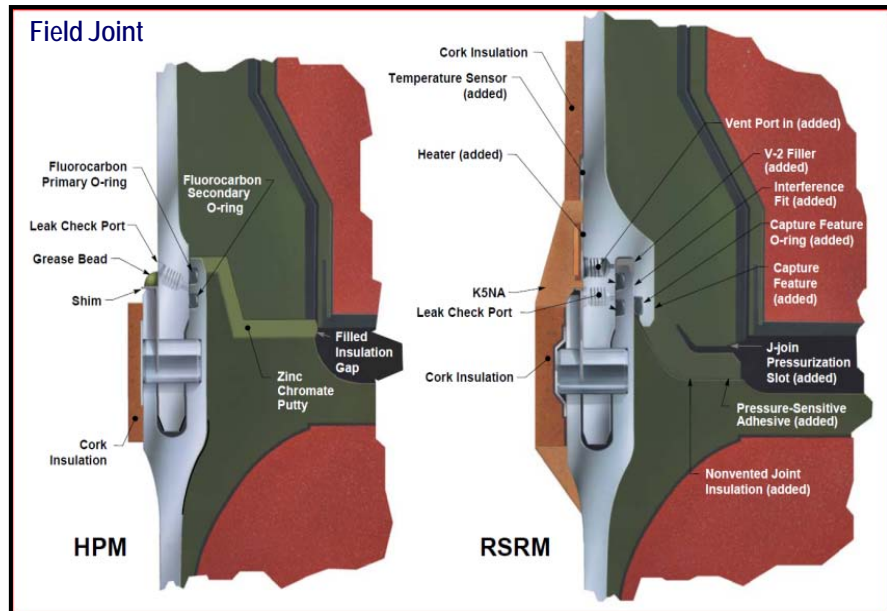


Takeaway Success: J-leg performance has been exceptional, not only has it performed its intended thermal barrier function, it has also never allowed gas into the joint (except for RSRM-55 special cause)

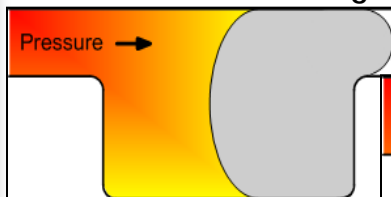
Nozzle-to-Case Joint



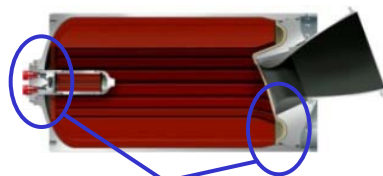
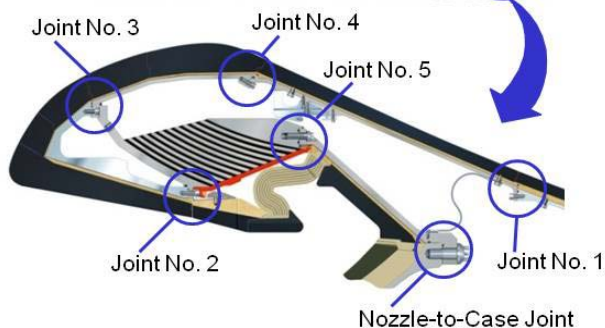
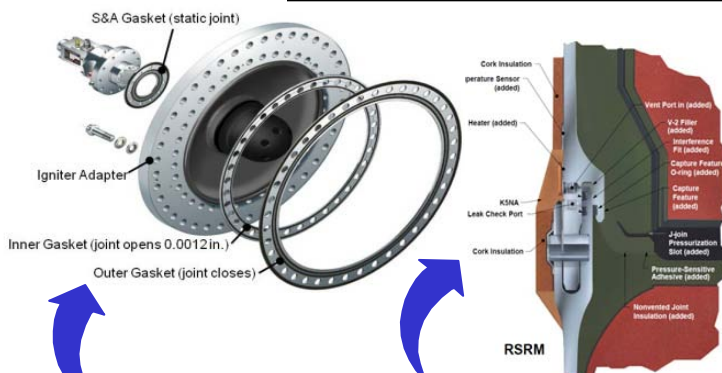
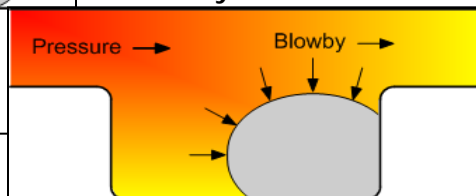
Field Joint



Successful Tracking

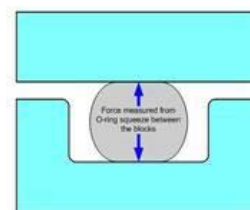


Blow-by Failure

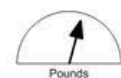
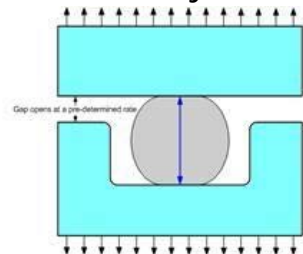


BSM O-Rings

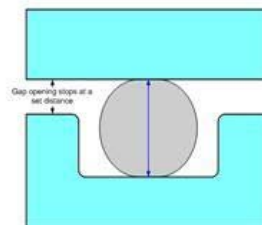
Resiliency Testing



Pre-Test, the internal (resiliency) force of the O-ring is at its maximum, in conjunction with squeeze



During Testing, the gap opens at a pre-determined rate. As squeeze is reduced, the O-ring exerts less and less force between the blocks

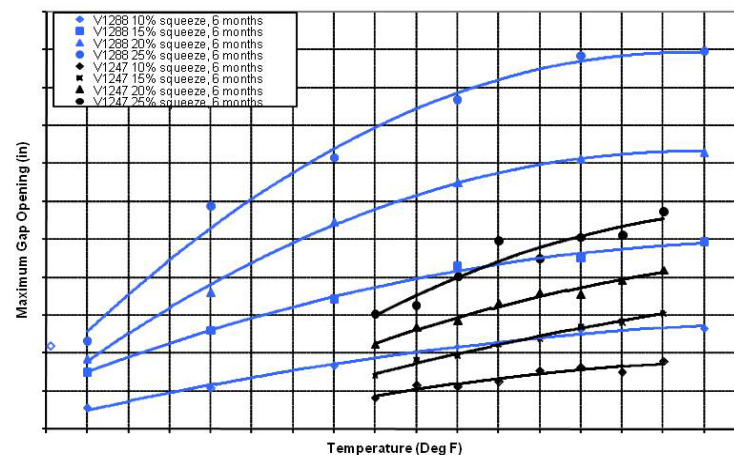


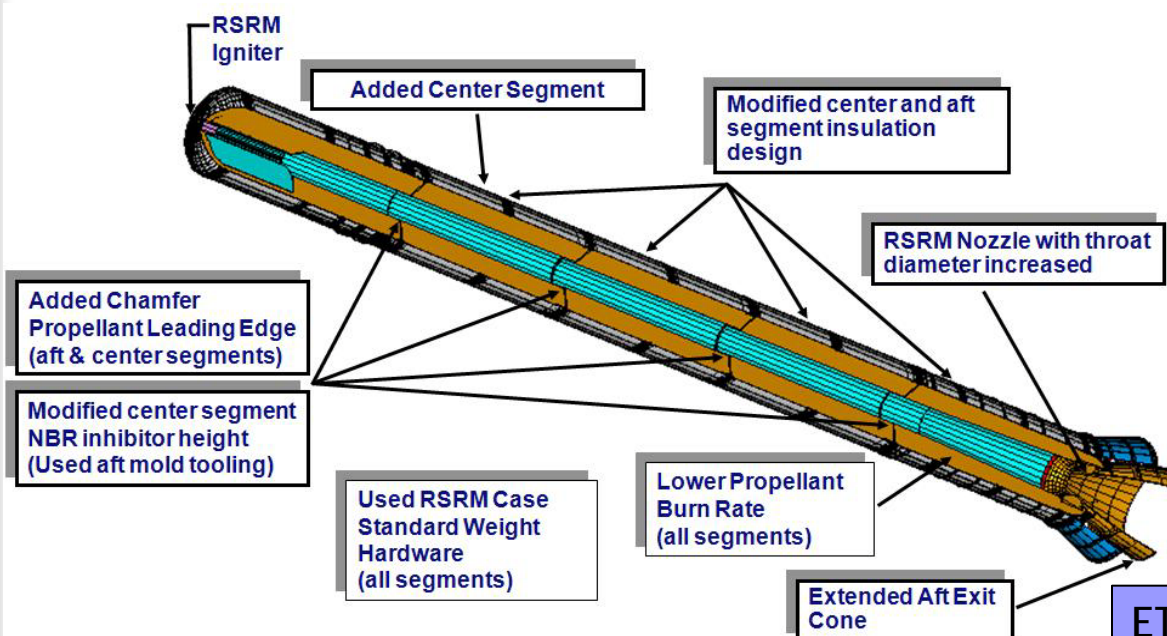
As testing finishes, the minimum resiliency force is determined

Major Findings from Testing

- ◆ Case field joint O-ring tracking margin at 41° F for improved resiliency V1288 is the same as V1247 at 81° F
- ◆ V1288 erosion rate is 50% less than V1247
- ◆ All other physical properties and characteristics meet V1247 requirements

O-RING RESILIENCY DATA V1288 vs. V1247





Conditions more severe than RSRM

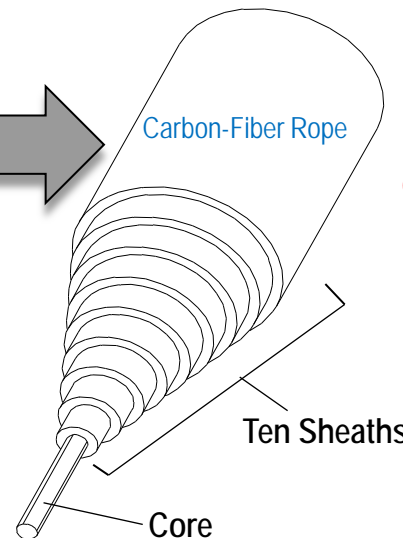
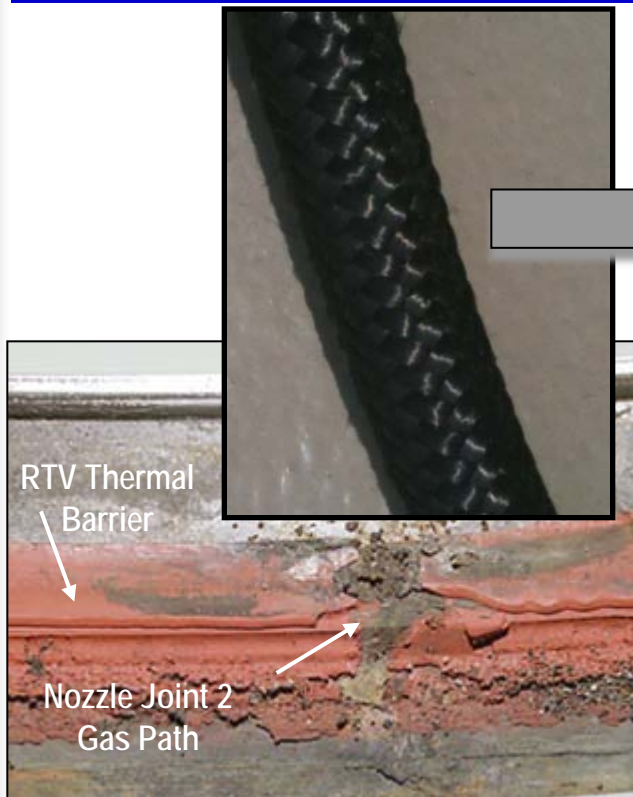
- ◆ Thermal environment
- ◆ Structural loads
- ◆ Erosive burning
- ◆ Acoustic activity
- ◆ Slag
- ◆ Burn time
- ◆ Mass flow and mach number
- ◆ Pressure and pressure drop
- ◆ Buckling and joint loading
- ◆ Increased length and fill volume for the igniter

ETM-3 was instrumented with 620 gages and 635 total channels

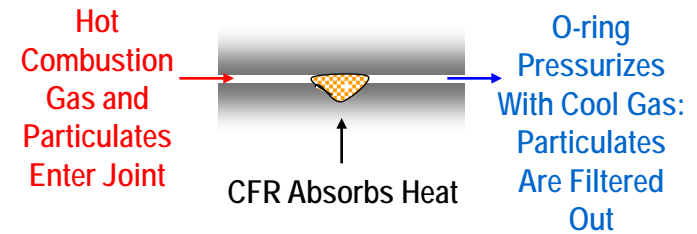
Benefits

- ◆ ETM-3 demonstrated robust margins for RSRM
- ◆ Learning experience and challenge for the NASA/ATK workforce (design, build and test a new motor from scratch)
- ◆ ETM-3 success was a great step toward Ares/RSRMV five segment motor development

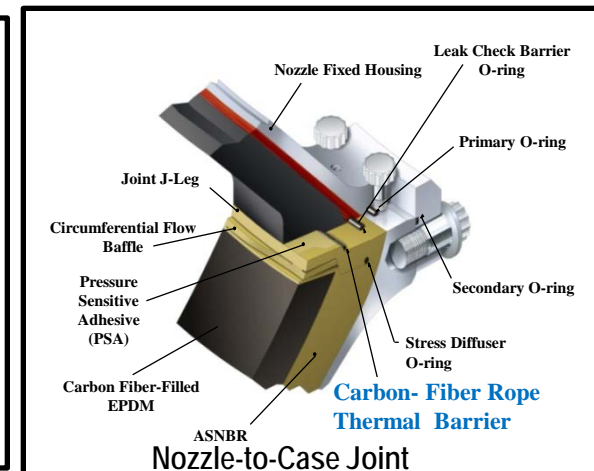
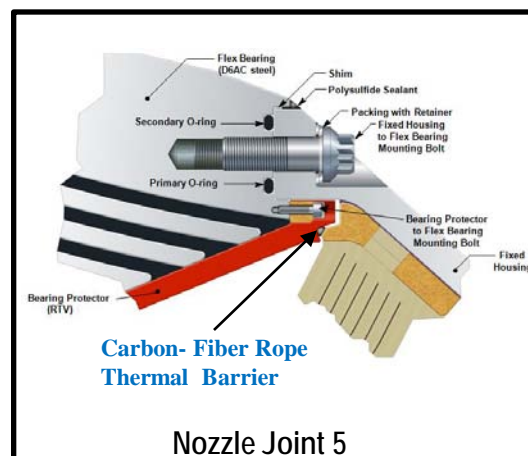
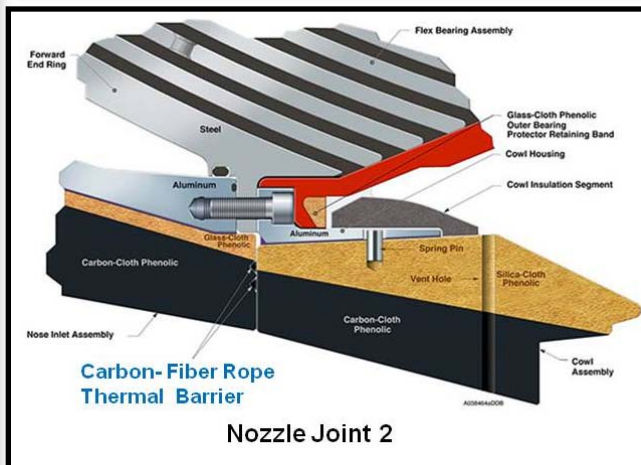




CFR Heat Exchange Concept



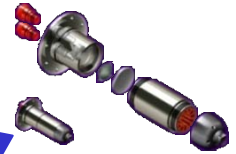
A change in paradigm (pressurized joints) led to significant design improvements that enhanced thermal margins and eliminated a potential failure mode



Improvements



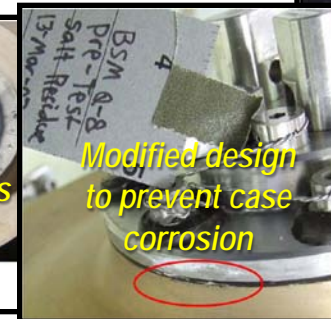
- ◆ Interchangeable fwd and aft motors
- ◆ Sling lined chamber
- ◆ Batch cast vs. continuous flow production
- ◆ TIGA adhesive (RSRM baseline)
- ◆ Graphite throat redesign to improve margins
- ◆ Interchangeable metal hardware—eliminates matched sets
- ◆ Increased O-ring squeeze
- ◆ V-1288 low temp O-ring material
- ◆ Igniter-to-case leak test port added
- ◆ Redesigned Igniter



Qualification Test Matrix

Test Motor	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Propellant Mix Configuration	D	D	D	C	C	C	C	A	A	A	A	B	E	B	B
Fwd BSM	X	X	X	X		X				X	X	X	X		
Aft BSM					X		X	X	X					X	X
Redundant															
One CDFI	X	X													
Two CDFI			X	X	X	X	X	X	X	X	X	X	X	X	X
All O-rings	X	X	X					X	X	X	X	X	X	X	X
Outboard O-ring Only						X	X								
No O-Rings				X	X										
Test															
Product Examination	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Thermal Cycling								2	2	2	2	2	2	2	2
Altitude Cycling								3	3	3	3	3	3	3	3
45 Day Aging															
-10°F	2														
+130°F		2	2												
Rain								4	4	4	4	4	4	4	4
Salt Fog								5				5			
Humidity								6	5	5		6		5	
Vibration															
Lift-off								7	6	6	5	7	3	6	5
Boost								8	7	7	6	8	4	7	6
Ordnance Shock											7				7
Altitude Start	3	3	3												
Low-Temp (30°F)	4	4	4		2	2		9			8	9		8	
High-Temp (120°F)				2			2		8	8			5		8
Plume Particle Collection	X	X	X	X	X					X	X	X	X		

Takeaway Success: It took an exceptional effort and great teamwork by ATK to certify, build and fly BSM hardware in only 19 months



RSRM Lessons Learned

FRED PERKINS

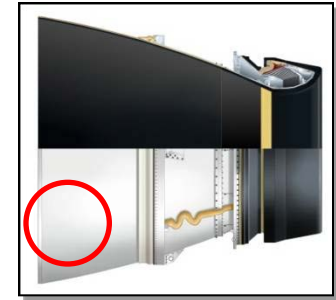


- ◆ Nozzle Pocketing
- ◆ Field Joints and Nozzle-to-Case Joint
- ◆ Pressure Sensitive Adhesive
- ◆ RSRM Evolved Toolbox



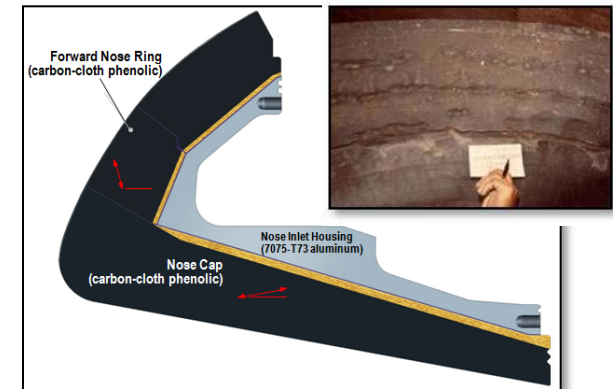
♦ Background

- Carbon-Cloth Phenolics (CCP) form the nozzle contour and protect underlying structure
- CCP wrapped on a mandrel, cured and machined to a final profile



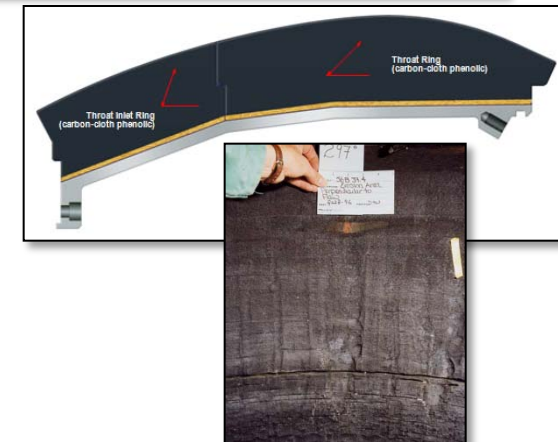
♦ Observation

- Pocketing occasionally observed in nose and throat
- Seemingly “random” behavior indicated subtle variability
- Behaviors not observed during certification/verification testing
- Work as a result of STS-8 nose pocketing led teams to believe problem understood and rectified via nose ply angle change
- Subsequent, STS-51D exhibited similar behavior in throat region



♦ Resolution

- Root cause determination and corrective action worked in iterative phases – tendency to assume the problem solved until new occurrence
- Design ply angles, processing, material screening, higher carbonization temperature – Changed in separate waves of corrective actions



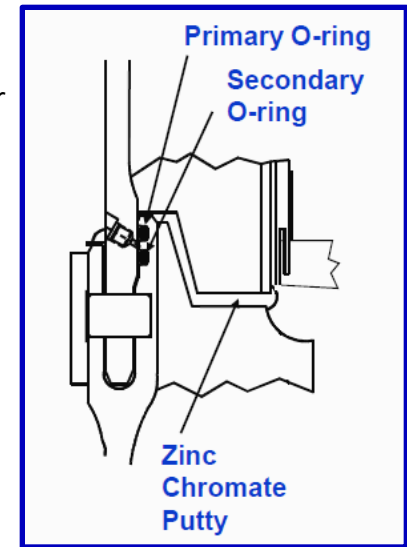
Lesson Learned – Robust root cause analysis essential to comprehensive understanding. Subtle effects of material/process variability on performance must be understood and verified. Controls sufficient to verify material/process variability within certified range

♦ Background

- SRM (pre-RSRM) used putty between the motor segments as a thermal barrier
- Assembly process could leave vent holes through the putty
- Joint movement from ignition sometimes caused “blow-by” of the seals

♦ Observation

- Blow-by occurred in the primary seal locations of the SRM field joints and nozzle-to-case joint – erosion of O-ring was not design intent
 - Team accepted performance inconsistent with design intent
 - “Hardware was talking”
 - Weak CoFR process – selling as opposed to risk disclosure
- Team understood that the primary seal could fail but were convinced that the secondary seal would hold
 - Common cause failure (O-ring material low temperature resiliency and dynamic tracking) resulted in joint failure and loss of Challenger crew



STS 51-L Design

♦ Resolution

- Robust joint redesign – addressed gas path to O-ring, fill volume, O-ring tracking (geometry, gap opening, and resiliency), thermal protection system
- Robust certification process – subscale and combined loads full-scale test, analysis and fault tolerance
- CoFR process based on risk assessment and communication/sharing

♦ No gas to primary O-rings since redesign (over 700 total joints flown/tested)

Lesson Learned – Robust root cause determination, corrective action, certification process (including off-nominal and fault tolerance) result in robust flight design

♦ Background

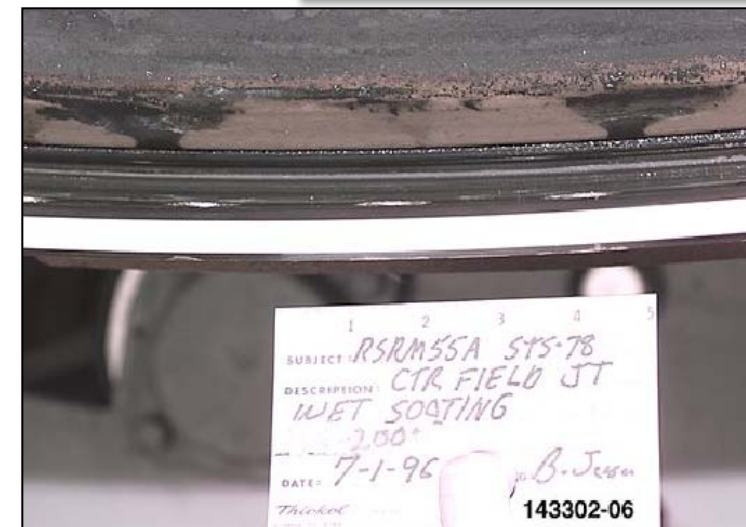
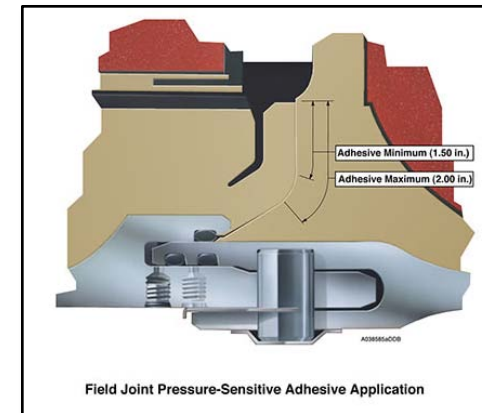
- RSRM redesigned field joints include J-leg interference fit thermal barrier as first leg of joint seal thermal protection system
- RSRM redesigned field joints performed as designed on first 300 joints flown

♦ Observation

- Hot gas penetrated past the tips of all six J-legs on RSRM-55 (STS-78) launch in June 1996
 - Out-of flight family performance
 - New ODC-free pressure sensitive adhesive used for the first time on RSRM-55
 - Adhesive had worked perfectly in a full-scale static-test motor fired in Utah

♦ Resolution

- RSRM-54 (STS-79) utilized same PSA – de-stacked
- Environment at Kennedy Space Center (high humidity) reduced the peel strength of the adhesive; peel strength was key to keeping the J-leg sealed. In addition, the design team believed the J-leg would seal without any adhesive
- The immediate fix was to return to the baseline adhesive
- Long-range actions included extensive subscale and full-scale testing, plus thermal and structural analysis to understand in detail, the J-leg response to processing and operating environments



Lesson Learned – Test what you fly. Testing ideally to include all operating environments and parameters. Identify and assess risk (FMEA) of flight attributes/interactions not explicitly tested

- ◆ **Several Key Factors in Achieving and Maintaining Excellent Flight Performance**
 - Robust Process Control
 - Statistical process control – Identify and disposition within-engineering but out-of-family data
 - Fingerprinting of materials – Allows identification of subtle changes in the supplier chain
 - Extensive use of PPIA audits (stamp warranty) both in-house and at suppliers
 - Process sensitivity testing – Design of experiments, corners of the box testing, etc.
 - Emphasis with suppliers on change identification
 - Comprehensive change verification process
 - Fault Tolerant / Failsafe testing and analysis
 - Enhanced analytical models and material databases
 - Models anchored to test
 - Yearly full-scale static testing
 - Rigorous anomaly investigation/resolution and root cause analysis (listen to the hardware)
 - Structured postflight teardown and inspection prior to a subsequent flight
 - Rigorous certification of flight readiness process (understand and communicate risk)

Conclusion – The RSRM program has learned from past events and evolved an extensive toolbox of techniques, practices, and systems designed to ensure the configuration and integrity of each RSRM flight set before flight

RSRM Culture

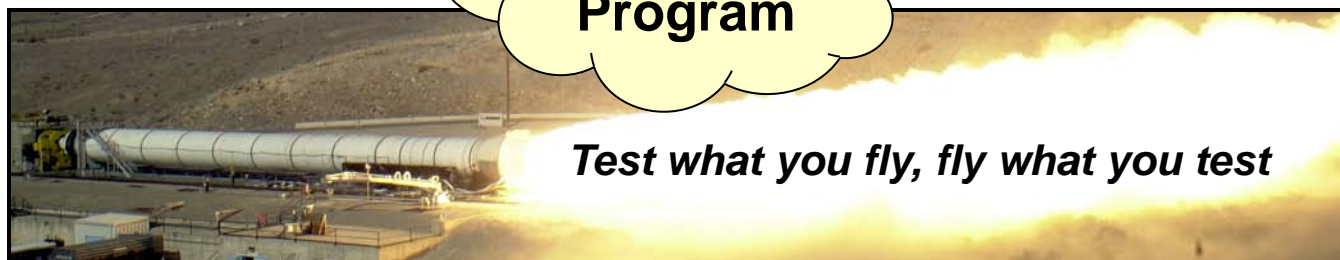
DENNIS MOORE



- ♦ RSRM Test Program
- ♦ RSRM Postflight
- ♦ 7 Elements of Good Flight Rationale
- ♦ Some Thoughts on Minority Opinions
- ♦ Summary



- ◆ The RSRM is the highly reliable rocket motor it is today due to constant vigilance and focus on the necessary elements of RSRM flight safety
 - ... these elements are key to the successful culmination of the Space Shuttle Program



Test what you fly, fly what you test

Subscale Solid Rocket
Test Motor (SRTM)



5 Inch Propellant
Center Perforated Subscale Testing



Subscale MNASA Motor



Flight Support Motor



Insulation Witness Panel
Subscale Testing



Igniter Testing



Propellant Dog Bone Testing

Test Summary

- ◆ **Material/Process Change Categories**
 - Obsolescence
 - Improvements – Implementing better materials/methods or reacting to postflight observations
- ◆ **Typical Process for Evaluating Significant Changes**
 - Multiple candidates screened by least expensive testing (dog-bone type)
 - Down-selected candidates to sub-scale hot-fire
 - Best Candidate selected for FSM demonstration/qualification
- ◆ **FSMs tested were tested about 1 per 12-month cycle**
 - Highly instrumented – can detect subtle drifts
 - Many changes typically on any one FSM
 - Changes had to be evaluated for conflicting objectives
- ◆ **FSM tests evolved from original intent of testing production line motor to being the Change Precursor**
 - Combined with our level of Postflight makes up for inability to “Green Run”

Launch



Retrieval



Open Assessment



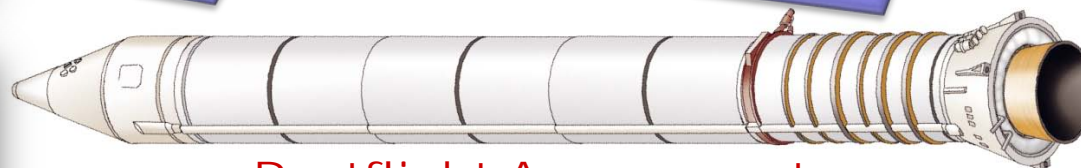
BSM Assessment



Nozzle Assessment



RSRM



Postflight Assessment



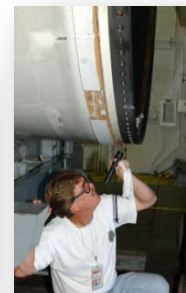
Insulation & Case



Nozzle Internal Joints



Return to Utah



Field Joint Evaluation



Igniter Assessment



◆ Postflight Team

- ATK DEs, MEs & QEs (responsible for hardware)
- MSFC Project/Engineering/S&MA

◆ Postflight Task



- Thoroughly evaluate and document hardware condition
- Identify, assess, and document reportable conditions and items of interest

Disciplined approach to evaluating hardware, dispositioning findings, and identifying IFAs

Approach is unique in SRM Industry

- ◆ **Solid technical understanding**
 - Physics based or root cause understanding of issue, based on engineering data (perhaps using a fault tree)
- ◆ **Condition relative to experience base**
 - Experience base includes full-scale flight, ground test, or qualification level tests
- ◆ **Bounding case established**
 - Using physics based understanding, determine the bounding case (e.g., lower A-basis allowables, upper three sigma loads and environments, anchored with test data)
- ◆ **Self limiting aspects**
 - Physical reasons why it can't get any worse than the bounding case or show the part is fail-safe
- ◆ **Margins understood**
 - Adequate margins, ideally not substantially reduced from baseline
- ◆ **Assessment based on data, testing and analysis**
 - Final risk assessment based on test data and analysis, not gut feel or expert opinion
- ◆ **Interactions with other elements/conditions addressed**
 - Address interactions with other conditions (MRB, changes, technical issues), and vehicle elements


Implemented 2001



RSRM CULTURE


7 ELEMENTS OF GOOD FLIGHT RATIONALE

DENNIS MOORE



Worksheet Example

Current State	Strong	Mod	Weak	Mitigating Actions
Solid Technical Understanding Unbond results from operator variability and tool differences Maximum extent possible unbond not known	← X			<ul style="list-style-type: none">• Complete statistical analysis of measured void distribution• Complete corner-of-box unbond testing
Condition Relative to Experience Base No known unbonds in previous flight article but assumed since process relatively unchanged			X	<ul style="list-style-type: none">• None
Bounding Case Bounding case structural analysis TBD	← X			<ul style="list-style-type: none">• Complete statistical analysis of measured void distribution• Complete high rate capability button testing• Complete loads survey• Complete stress analysis
Self-limiting Concern that non-bond size bounding case has not been captured Impact of stress risers due large non-bond regions not quantified	← X			<ul style="list-style-type: none">• Complete statistical analysis of measured void distribution• Complete high rate capability button testing• Complete loads survey• Complete stress analysis
Margins Current margins unknown	← X			<ul style="list-style-type: none">• Complete statistical analysis of measured void distribution• Complete high rate capability button testing• Complete loads survey• Complete stress analysis
Assessment based on Testing, Data, Analysis Based on analyses and test data Extensive capability database New analysis methodologies Reduced conservatism	← X			<ul style="list-style-type: none">• Complete analyses• Complete measurement and mapping of available bonded tunnels
Interactions with other Conditions/Components No known interactions except age – no age effects identified	X			<ul style="list-style-type: none">• None



RSRM - 23

Benefits from 7 Elements Approach

- ◆ Can be used to assess multiple types of issues
 - Technical Issues
 - Design Changes
 - MRB Items
 - Postflight Anomalies
- ◆ Clearly identifies Flight Rationale Strengths and Weaknesses
- ◆ Focuses on the facts
 - Removes emotion from characterizing risk
- ◆ Provides a “roadmap” when implemented early

- ◆ **Seek out minority opinions**
 - Silence doesn't always mean agreement – a lot of thinkers support us
 - Don't allow any fence sitters
- ◆ **Have a team of folks listen carefully – Hear Them Out**
 - Pull in some help from expert(s)
 - Avoid arguing or making counterpoints until they've been heard out
 - Keep in mind they could be right
- ◆ **Make a decision and tell them how you got there**
- ◆ **Be an advocate for the minority opinion**
 - Encourage and offer to take it forward
 - Use the management chain
- ◆ **Allow folks to change their minds**
 - New data or new way of thinking

- ◆ **RSRM is a highly reliable human-rated Solid Rocket Motor**
 - Largest diameter SRM to achieve flight status
 - Only human-rated SRM
- ◆ **RSRM reliability achieved by:**
 - Applying special attention to Process Control, Testing, and Postflight
 - Communicating often
 - Identifying and addressing issues in a disciplined approach
 - Identifying and fully dispositioning “out-of-family” conditions
 - Addressing minority opinions
 - Learning our lessons

*We look for weaknesses and figure out how to improve as a
RSRM NASA/ATK team*